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Radiation Hardening of Gated X-ray Imagers for the National Ignition Facility [a)]

P.M. Bell[1], D. K. Bradley[1], J.D. Kilkenny[2], A. Conder[1], C.Cerjan[1], C. Hagmann[1], D. Hey[1], N. Izumi[1], J Moody[1], A Teruya[1], J. Celeste[1], J. Kimbrough[1], H. Khater[1], M.J. Eckart[1], J. Ayers[1]

[1]Lawrence Livermore National Laboratory, Livermore, California 94550, USA

[2]General Atomics, P.O. Box 85608, San Diego, California 92186-5608 USA

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The National Ignition facility will soon be producing x-ray flux and neutron yields higher than any produced in laser driven implosion experiments in the past. Even a non-igniting capsule will require x-ray imaging of near burning plasmas at 10^{17} neutrons, requiring x-ray recording systems to work in more hostile conditions than we have encountered in past laser facilities. We will present modeling, experimental data and design concepts for x-ray imaging with electronic recording systems for this environment. A novel instrument ARIANE (Active Readout in a Nuclear Environment) is described which uses the time-of-flight difference between the gated x-ray signal and the neutron which induce a background signal to increase the yield at which gated cameras can be used.

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[b)]Electronic mail: bell11@llnl.gov

I. INTRODUCTION

The National Ignition Facility NIF is the world's largest laser driven fusion facility. It began 192-beam operation in 2009 [1] with deliberately low DD neutron yields of ~$1x10^{10}$, but will be producing large (>10^{17}) yields of DT neutrons as part of the ignition campaign. The full thermonuclear yield is about 20 MJ. The harsh environment generated by the thermonuclear output can induce large backgrounds or permanent damage on instruments used to diagnose or control the implosions. In addition to the damaging effect of primary neutron on instruments there are large effects from scattered neutron. Whilst propagating through the target chamber and experimental building, a large fraction of these neutrons will produce gamma rays by inelastic nuclear reactions. In a few hundred nanoseconds, the entire experimental building enclosed inside the bio-shield to protect facility workers will be filled with a mixture of 14 MeV and down-scattered neutrons and gamma rays up to a few MeV [2].

In the 2009 NIF implosions [1] gated x-ray detectors [3] were the primary diagnostics of implosion performance. They are used to assess the x-ray performance (size, symmetry, bang time and burn history) of imploding targets. Fast gate times are needed to avoid motional blurring due to the high velocities and small spatial dimensions of the imploding targets. High-speed image gating is accomplished by applying a short duration voltage to a Micro Channel Plate (MCP) [4]. Photons incident on the front surface of the array generate electrons, which are swept through the micro-channel pores by the high electric field. As a result of collision with the pore walls, additional electrons are liberated in this process and the device produces gain for the duration of the applied electrical pulse.

In early operation of NIF there has not been a major issue with the production of a background on the instruments caused by neutrons. For example, the gated cameras (called GXD)[2] used on NIF in 2009 were run with the detector at a distance of 1.2M from target chamber center (TCC). Although the detector package is well screened against x-ray and electrical backgrounds, it has negligible neutron screening. The GXD, when run on low yield DD shots on NIF in 2009, showed little sign of background from down scattered neutron events.

The general issue of hardening of instruments in the harsh environment of an ignition facility has been addressed [5] in previous conferences. A solution discussed in reference [5] is neutron and gamma shielding and transfer of information to a quieter environment. In this paper, we build on this work and explain how to use the delayed arrival of the background neutrons to record the signal of interest.

This paper is organized around the three regimes of neutron production on NIF and the limitations of their gated x-ray imagers.

II. THREE PHASES OF HARDENING OF GATED X-RAY CAMERAS ON NIF

The basic building blocks of the x-ray detector of a gated x-ray camera are shown in Fig.1. The MCP is gated on for the x-ray pulse of interest but is off for the neutron burst. The main neutron induced background caused by secondary effects comes from the fiber-optic faceplate, phosphor, and optical recording device (film or CCD). Long-term damage on electronic components also needs to be considered.

There are three regimes of neutron production on NIF as shown in table1. For low yields (~ 10^{10}), we use a GXD [6] where (1.2 meters from TCC) the CCD detector is most sensitive to neutrons and limits operations to about 10^{13}. Replacing the CCD with film allows for operation at up to yields of about 10^{15}. For higher yields, we are developing the technique of reading out the x-ray induced optical signal from the phosphor[9] onto a shielded and gated optical camera before the neutron induced signal arrives, allowing for the signal to be recorded with a low background by the gated optical detector CCD.

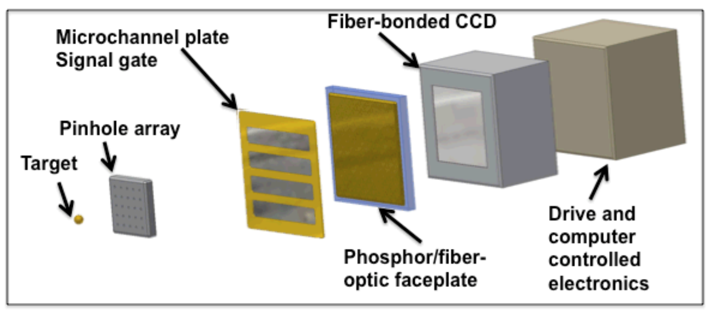

FIG. 1. Principal components of the gated x-ray detectors

Yield at TCC	MCP integration time	Phosphor Decay Time	Optical Recorder	Diagnostic Name
$Y_n < 10^{13}$	100ps	slow	CCD	GXD
$10^{13} < Y_n < 10^{15}$	50-100ps	slow	film	hGXI
$Y_n < 1015$	50-100ps	< 140 ns	130 ns gated intensifier to shielded CCD	ARIANE

TABLE1: Summary of the three phases of gated x-ray imagers on NIF

The three phases of gated x-ray cameras are shown in Table 1 and Fig 2, for the different type of implosions planned for NIF. DD neutron-producing shots can be measured with the existing GXD[6]. In 2010, the first DT implosions will have a low concentration of deuterium fuel (but with hydrogen and tritium) and will produce a yield in the range ~10^{14} to 10^{15}. In this regim, a film recorded gated x-ray camera, (hGXI)[7] can be used as described in section IV. Once the deuterium fraction in the fuel is increased, we expect the yield will increase above 10^{15} up to 10^{18}. In this regime, gated x-ray imaging can still be used but a higher level of screening is needed. A combination of screening and a novel use of the time-of-flight difference between the x-ray signal and the neutrons will be used with an active readout system, ARIANE (active readout in a neutron environment). The operation of the CCD in ARIANE is allowed by a combination of moving the detector outside of the NIF target chamber wall, (using the difference in neutron and x-ray time-of-flight), and neutron screening of the CCD detector.

The principal features of the three gated x-ray detectors are as follows: For low yield (Y_n <10^{13}), the neutron induced background is caused by the neutrons interacting in the most sensitive component, which is the CCD detector. This device is called a GXD. To record at Y_n>10^{13}, the CCD must to be replaced by less sensitive film. This device is called an hGXI. Background in the hGXI is generated by neutrons interacting in the film and to lesser extent, in the phosphor. To operate at Y_n >10^{15}, the background induced by the neutrons in the phosphor is ameliorated using the time difference in the arrival of the neutrons and x-ray signal. By moving the detector back to 7 meters, the first neutrons arrive 140 ns after the x-ray signal. By using a fast phosphor (P46 or 47), most of the phosphor light induced by the gated x-ray detector signal can be relayed to a gated optical intensifier in front of a CCD in a neutron-shielded enclosure, before the neutrons arrive at the phosphor of the gated x-ray detector. Although the neutrons do cause an optical background on the phosphor of the GXD, the light cannot reach the shielded CCD because the optical intensifier is gated off before the background signal arrival. This device is called Active Readout In A Neutron Environment (ARIANE)

III. GXD OPERATION FOR Y_N < 10^{13}

In this regime, the neutron-induced background is dominated by interactions in the CCD, as detailed in an accompanying paper [8]. The background generation is parametized by the neutron fluence at the CCD. A GXD-like CCD (SI 1000[12]) has been tested at OMEGA over a range of neutron fluence up to 5.7x10^7 n/cm^2. This corresponds to a yield on the NIF of 3x10^{14} neutrons from TCC with the CCD at 1.2m from TCC. With advanced image processing software, usable data can be extracted up to 5x10^7 n/cm^2 in CCD data.

IV. HGXI OPERATION FOR 10^{13} < Y_N < 10^{15}

For higher yield targets, we remove sensitive electronics including the CCD and computer controls. Testing at the Omega laser[8] has shown that film is approximately 30x less sensitive than CCD to radiation and is therefore substituted for the CCD. The computer controls for most of the electronics[7] are also replaced by manual controls.

The background is produced by the phosphor, the fiber optics plate (FOP) and the film. Neutrons interact directly with the nuclei in the phosphor. The main interaction process in the FOP is (n,n')g with Compton electron generation. The main interaction process in the film is by charged particle interaction. The fraction each process contributes to total background is: Phosphor: 10%, FOP: 40%, film: 50%. It is shown in[8] that the signal to noise for contour determination drops from about 15 to <10 for Y_N > 10^{15} where the background level is approximately 10% of the saturation level of the film.

V. ARIANE OPERATION FOR Y_N > 10^{15}

Operation at higher neutron yield is fundamentally limited by neutron interactions to approximately 10^{10} n/cm^2. The x-ray brightness of the core image in these experiments is significant, so the detector package 'can be' moved further back from TCC. However, with film as the readout, operation above 10^{17} even at 7 meters, is limited by background. Moreover, outside of the target chamber, but inside of the 2 meter thick concrete Bio-wall of the target chamber building, the neutron fluence does not drop simply as 1/r^2 because of late time scattering of neutrons in the target bay and off the wall of the target chamber building. Essentially the building has become a neutron hohlraum[9] and at 10^{17} primary neutron yield, the fluence at the detector is ~10^{11} n/cm^2 because of the scattering.

Another advantage of moving the detector further back is that the time difference between the arrival of the x-ray signal and the slower 14 MeV DT neutrons increases. Unlike the neutron background, this does scale with distance from TCC. By choosing a distance of 7 meters from TCC, the x-ray signal arrives ~ 140 ns before the primary neutrons, which is longer than the decay time of some of the faster phosphors [9]. For the GXD and the hGXI, the phosphors are P43 and P11 respectively with decay times > 1 ms. Phosphors with decay times ~150 ns are P46 (0.66 140 ns fraction) or P47 (0.96 140 ns fraction). There is a trade-off in color output and brightness linked to optical transmission and optical intensifier quantum efficiency. We will study these features for our gated detectors in the near future.

The x-ray layout of the ARIANE is shown in Fig 3. The x-ray power emitted by an implosion is ~ 5TW over approximately 200 ps from an object with a 25 micron radius, with the x-ray spectrum peaking about 12 keV. The GXD detectors on NIF [2] have used an array of pinholes 10 micron in diameter in 70 microns of tantalum with a center-to-center spacing of 200 microns. For GXD, the magnification is 15x, with a pinhole array standoff of 80 mm from TCC. The array of pinholes relaxes the alignment specification. The ARIANE standoff distance forces its pinhole array to be drawn back to 270 mm to ensure the magnification is not too large. However, the brightness of the source ensures we will have 1400 photo-electrons per 250 micron pixel using scaling from previous experiments on NIF[3]. Light from the x-ray framing camera is relayed to a CCD recording system located inside a shielded box. [The shielded CCD will have a gated optical intensifier in front of it. This will be gated off before the background light arrives from the neutron interaction with the gated x-ray detector and the fluorescence background from relay optics arrives. We calculated the throughput for three optical relay concepts from the gated x-ray detector to the optical detector: a 15 foot fiber bundle, an f/3 relay and an f/1.2 relay. All have adequate transmission in concept.

The directional gamma and neutron flux at the detector is calculated using a very detailed model in MCNPX[11], including the structures contained in the target bay.

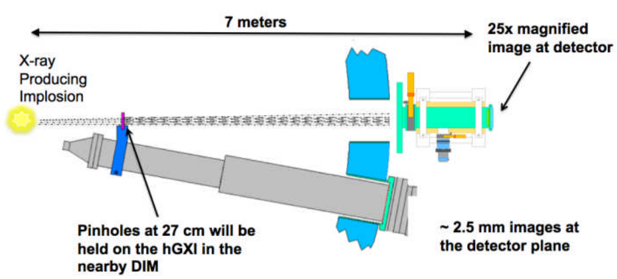

FIG. 2. The x-ray layout of the ARIANE gated x-ray camera.

With no shielding, the fluence at the gated CCD is orders of magnitude higher than the level that would saturate the detector. Calculations of energy deposition in the Si predict that there would be up to a hundred stars (saturated events) per pixel[10]. Using a combination of low Z material (for neutrons) and high Z material (for gamma rays) screening, we calculate that the flux can be reduced to ~5×10^7 n/cm^2 inside a shielding box with a mass of about 3 tons.

A detailed calculation of the energy deposition in the CCD indicates that the number of affected pixels are now down to ~10%. The cavity has volume of ~30 liters, which is sufficient for the CCD and necessary electronics at yields up to 10^{17}. There is an inner Pb shield thickness of ~15 cm, covered with an outer borated Poly shield thickness of ~30 cm. There is an additional 30 cm of Poly on the side facing the TCC. The mass is approximately 1.2 tons of Poly and 2.1 tons of Pb. This total mass is well within the limits of the target bay location.

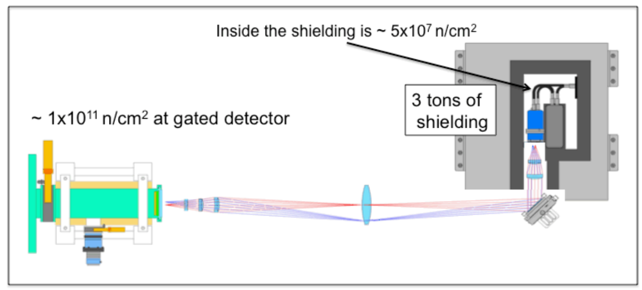

FIG. 3. The layout of the optical read out of ARIANE.

Finally, there are two concepts allowing for operation at a higher yield, up to the full 20 MJ design yield of the NIF. Film behind the optical intensifier will clearly work up to >30x higher fluences than the CCD. However, there are operational issues associated with extracting the film in this environment. We are in the process of developing a dump and read recording concept. We will use a long decay phosphor (100's of milliseconds) on the optical intensifier, which stores the signal of interest. While the neutron-induced background is present on the electronic recording device (100's of ns), we will electronically dump the neutron induced background. Once the background goes quiet, we wake up the electronic recording device and integrate the balance of the phosphor persistence from the intensifier.

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